PART II

SPATIAL AND TERRESTRIAL MONITORING OF ENVIRONMENT AND NUMERICAL SIMULATIONS

A. Herzog, T. Dubos, S. Turquety, D. Khorostianov

Improving our understanding of atmospheric chemistry, physics and dynamics is a necessary step to better assess the evolution of climate and the forcing by natural processes and human activities. For this purpose, constant monitoring at observation sites has been implemented, complemented in the past decades by space-borne instrumentation on board scientific satellites for a global view of atmospheric composition. To allow a precise interpretation of these observations, more and more accurate numerical models are developed for various applications, from weather and air quality forecasting at regional scales to climate evolution modeling at a global scale. The objective of this course is to introduce the basics concepts and give examples of the most recent advances in remote sensing of the atmosphere – both ground-based or space-based – and numerical modeling.

This course is divided into 2 parts:

1. Lecture on observation and modeling of the atmosphere
(A. Herzog, T. Dubos, S. Turquety)

2. One practical class to be chosen among the three following topics:
   - 2.a. Measure atmospheric particles with SIRTA lidars (A. Herzog)
   - 2.b. Analysis of satellite observations in the infrared for atmospheric pollution monitoring (S. Turquety)
   - 2.c. Simulate meteorology and chemistry with regional scale model (T. Dubos and D. Khorostianov)

The tutorials will use measurements collected at the SIRTA[1] observatory and InTro[2] modelling facility.

A summary will be prepared at the end of the day for the evening presentation and discussion session (day 2).

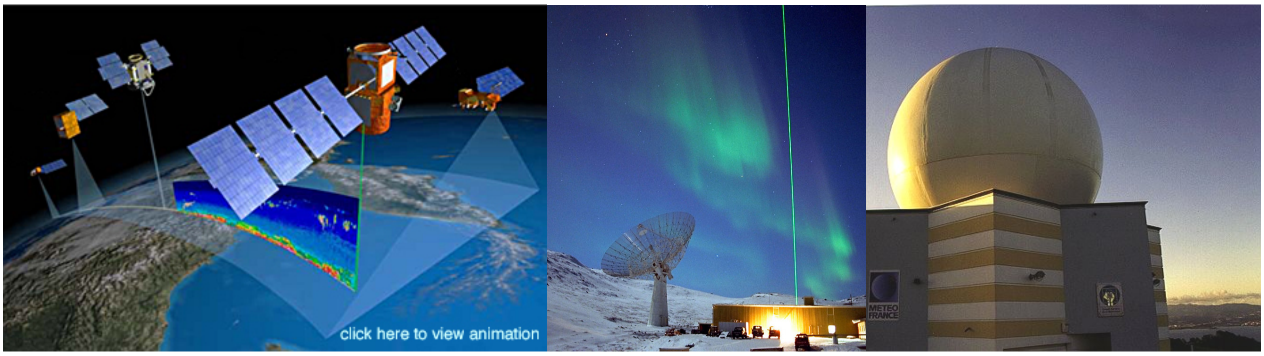
[1] SIRTA stands for Site Instrumental de Recherche par Télédétection Atmosphérique. It is a French national atmospheric observatory dedicated to cloud and aerosol research. SIRTA is located in Palaiseau (49N, 2E), 20 km south of Paris (France) in a semi-urban environment. The observatory gathers and operates a suite of state-of-the-art active and passive remote sensing instruments from a large community to document and monitor an ensemble of radiative and dynamic processes in the atmosphere. SIRTA is an observatory of Institut Pierre Simon Laplace (IPSL), a French research institute in environmental sciences. It is hosted by Ecole Polytechnique and supported by Institut National des Sciences de l'Univers (INSU/CNRS), Centre National d'Etudes Spatiales (CNES), Centre d'Enseignement et de Recherche en Environnement Atmosphérique (CEREA).

[2] InTro stands for "Interface of the Troposphere" research group (http://www.lmd.jussieu.fr/InTro)

Active Remote Sensing of the atmosphere

— Lecture by —

Albert Hertzog
Laboratoire de météorologie dynamique
Institut Pierre Simon Laplace



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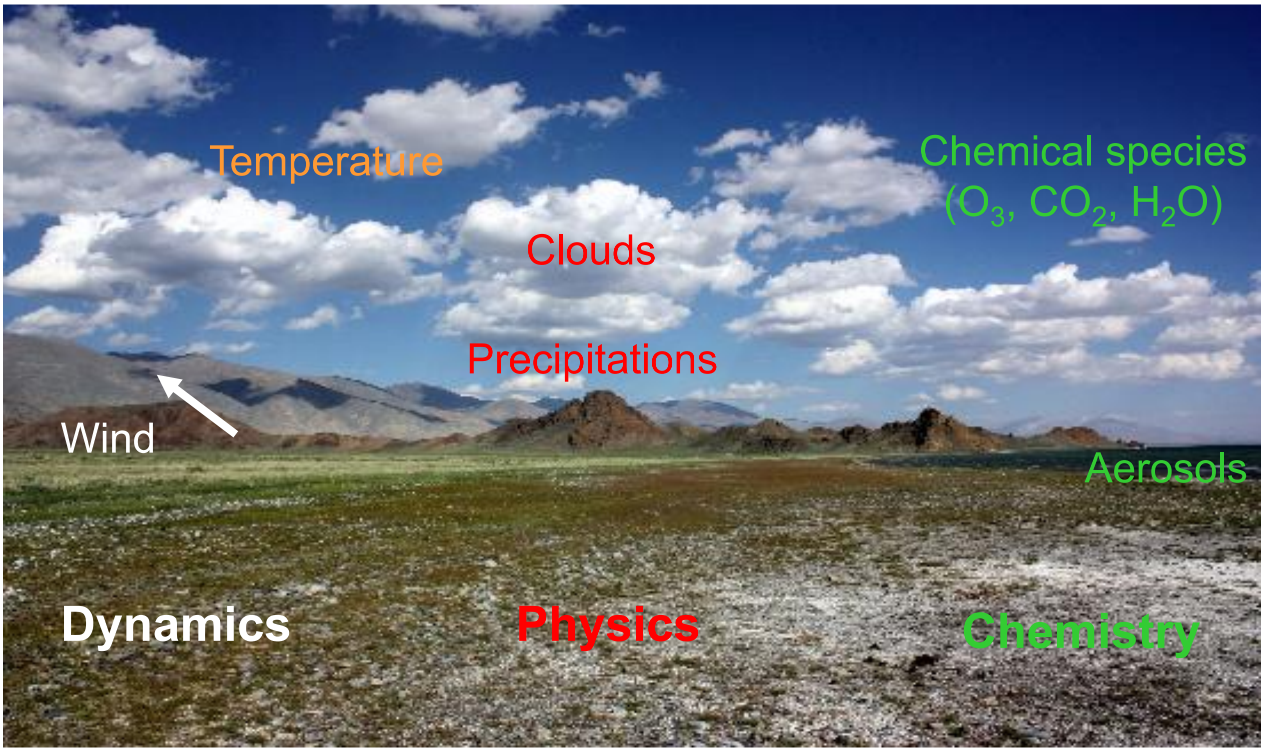
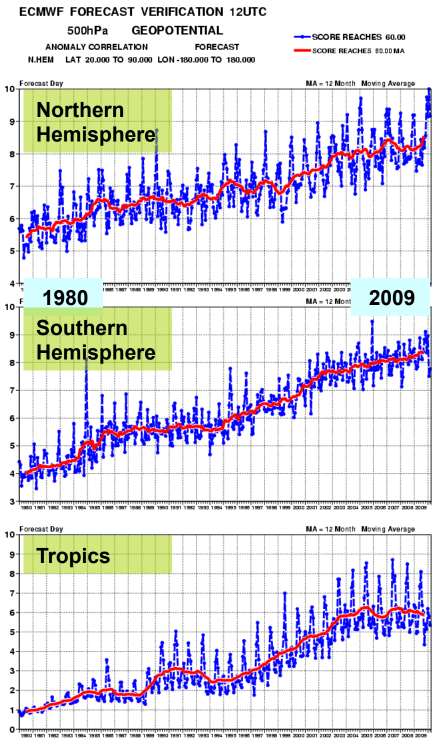
Many applications…



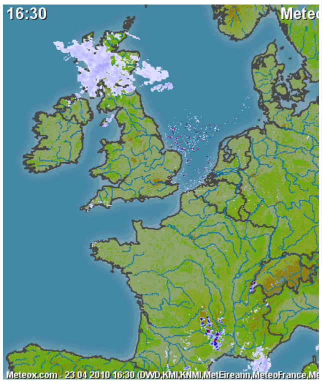
…and important impacts

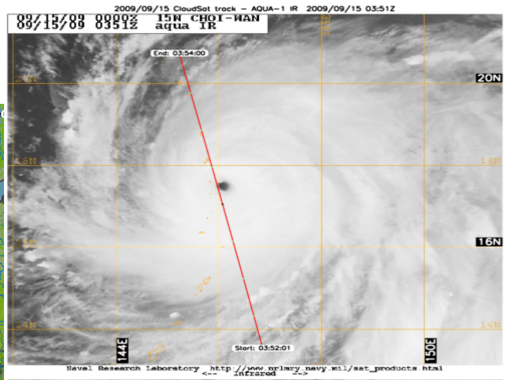


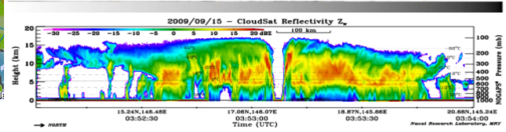
Long-term improvement of weather forecasts (through assimilation of global observations)

Short-term forecasts of meteorological events (natural hazards, weather-depending activities)

Improvement of our knowledge and understanding of atmospheric processes







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How active remote sensing is working ?

- Principle of measurement
  - An artificial (light, sound) wave source is directed toward the atmosphere by an emitting device
  - The wave propagates into the atmosphere, and eventually interacts with various targets: molecules in the gas phase (either N_2, O_2, or trace species), liquid water drop, ice crystals, liquid or solid aerosols…
  - The wave is « modified » because of this interaction with the atmospheric matter
  - A receiving device collects this modified wave, which contains some information on the state of the atmosphere
  - An analysis of the returned wave is done to retrieve the atmospheric information

Wave sources

- Choice essentially depends on the targets
  - Electro-magnetic (EM) waves
    - Light -> Lidar (Light detection and ranging) for molecules, small drops or crystals inside clouds, and aerosols
      - Ultra-violet (UV) : 200 nm < λ < 400 nm
      - Visible : 400 nm < λ < 800 nm
      - Infrared (IR) : 0.8 µm < λ < 10 µm
    - Radio -> Radar for drops, precipitations, and turbulent layers (from which winds can be deduced)
      - VHF : 1 m < λ < 6 m
      - UHF : 0.3 m < λ < 1 m
      - Centimetric (1 GHz < f < 30 GHz): meteorological radars
      - Millimetric (f ~ 100 GHz)
  - Acoustic waves
    - Sound -> Sodar for turbulent layers (from which winds can be deduced)
      - 10 cm < λ < 30 cm
- There are additional aspects
  - Polarization of the EM waves for instance

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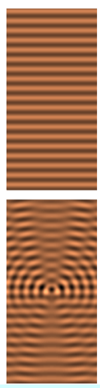
Wave interaction with the atmosphere

- There are 2 possible interactions (apart no-interaction)
  - Scattering
    - Redistribution in space of the emitted wave
    - Importance of the size of the scatterers (r) vs λ
      - r << λ : Rayleigh scattering : the scattering efficiency highly depends on the size of the scatterers (it increases with r)
      - r ~ λ : Mie-like scattering : the scattering efficiency slightly depends on the size of the scatterers, and is greater than for Rayleigh scattering
    - Additional effects can be used:
      - Polarization modification, wavelength shift (Doppler for wind, Raman for chemical composition)
    - Back-scattering is essential as the collecting device generally lies close the wave source.
  - Absorption
    - The energy of the emitted wave is transferred to the molecules (internal energy)



Top: plane wave propagating without interaction with the medium
Bottom: A scatterer modifies the wave energy distribution in space

The backscattered signal (1)

- Depends on
  - The emitted signal (power, wavelength)
  - The geometric distance between the receiver and backscattering layer
  - How the atmosphere is transparent (or opaque) for that wavelength
  - The number, size, speed, orientation of targets in the scattering layer
  - The receiving device
- Carry information about the state or composition of the atmosphere
- For instance, the lidar equation reads:

$$N(z,\lambda) = \frac{N_0 \, K \, \beta(z,\lambda) \, T^2(z_0 : z,\lambda)}{(z-z_0)^2}$$

N_0, N: number of emitted, collected photons
K: instrumental constant
β: backscattering coefficient
T: transmission function

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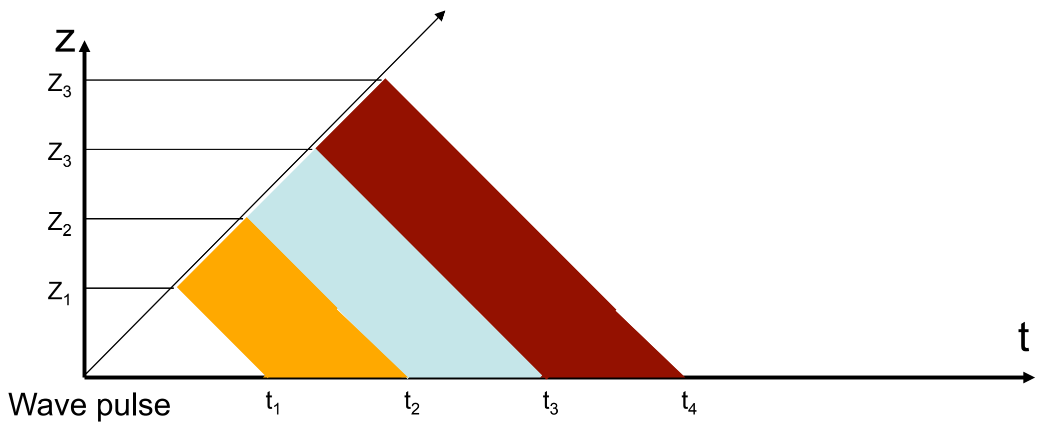
The backscattered signal (2)

- Carry information on how far away from the emitter/receiver the backscattering layer is located



$$Z_i = c \, t_i / 2$$

Sampling in time the returned signal is equivalent to sampling in distance (altitude) the atmosphere

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Analysis of the returned signal

$$N(z,\lambda) = \frac{N_0\, K\, \beta(z,\lambda)\, T^2(z_0 : z,\lambda)}{(z - z_0)^2}$$

$$\beta(z,\lambda) = \left(n_{mol}(z)\sigma_{mol}(\lambda)p_{mol}(180°) + n_{part}(z)\sigma_{part}(\lambda)p_{part}(180°)\right)\Delta z$$

Molecular signal (Rayleigh) Particular signal (Mie)

- Measuring power (number of photons in the case of EM)
  - Get information on the efficiency of backscattering/absorption processes in the atmosphere
    - Detection of aerosols and clouds (with λ > 300 nm)
    - When combining different wavelengths, information on the size of scatterers
    - In the absence of aerosols and clouds (Rayleigh Lidar), the backscattered signal is proportional to the number of molecules, from which the absolute temperature can be retrieved (thanks to the hydrostatic balance and the perfect gas law)
- Measuring difference in backscattered power with polarization
  - Get information on the shape of scatterers -> in particular, spherical scatterers do not change the polarization of the emitted wave

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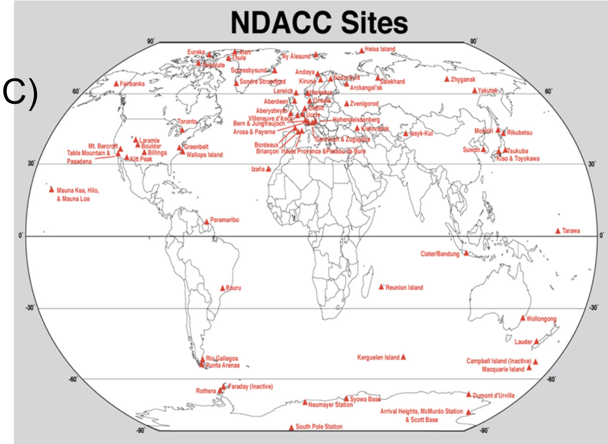
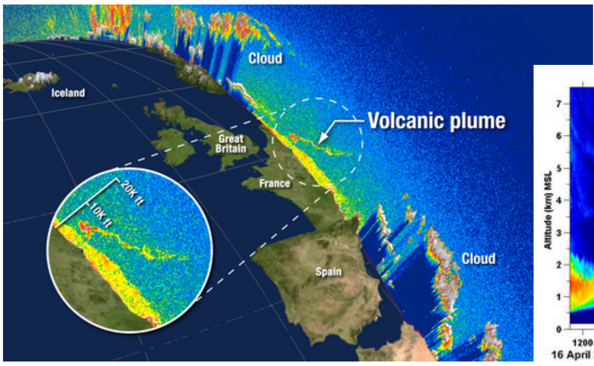
Analysis of the returned signal

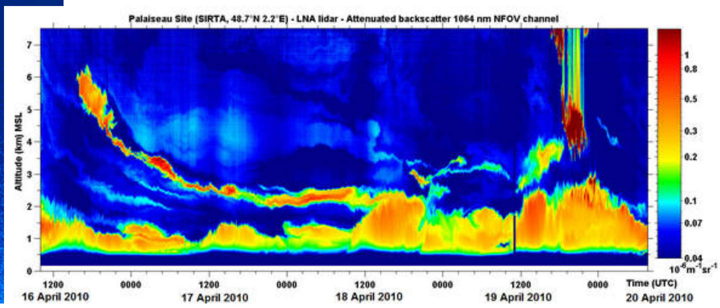
- Measuring frequency shift between emitted and received signal (Doppler)
  - Get information on wind projected on the beam line of sight
- Measuring difference between signals at two different (close-by) wavelengths (DIAL)
  - Get information on the presence of an absorber in the atmosphere (ozone, water vapour, carbon dioxyde, etc.)
- Measuring photons backscattered at other wavelengths than the emitted wavelength (Raman Diffusion)
  - Get information on the presence of a specific molecule (ozone, water vapour)

Some instruments, stations

- Gound-based stations
  Research and monitoring (e.g., NDACC)
- Airborne platforms
- Spaceborne platforms: A-train (Calipso and Cloudsat), ESA ADM/Aeolus and Earthcare
- Much on-going development (research, industry)







Observing Atmospheric Composition from Space
Lecture by S. Turquety

Objectives of this course:

- Understand the purpose of satellite observations of chemical species
- Introduction to the observation geometries and their complementarities
- Overview of current missions
- Introduction to the use of satellite products
- Examples
- Future of satellite monitoring for atmospheric chemistry

Practical work:

- Simulation of IR observations and sensitivity to key species
- Retrieval exercise: impact of key measurement characteristics
- Comparison of different observations

Analysis objectives:

- First steps in designing a future mission for atmospheric chemistry

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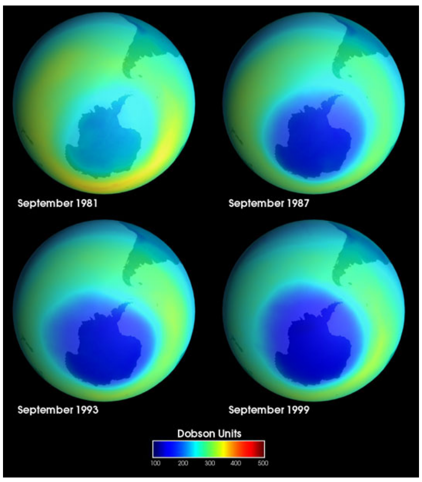
First observations of atmospheric composition

- **1st satellite : Sputnik in 1957 => Start of « space age »**
- **1st satellite for Earth observation missions launched in the late 1950's with the NASA Explorer missions**
- **1st weather satellite: TIROS 1 launched in 1960**

TIROS 1 (©NASA)



Total ozone observations since the 1970's

- nadir-viewing backscattered ultraviolet (BUV) on NASA Nimbus 4 (1970-1980)
- solar backscattered ultraviolet (SBUV) and the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7 (1978-1993).

Key in understanding the ozone hole formation

Recent missions mostly oriented towards tropospheric chemical composition, which will be the main focus of the course.

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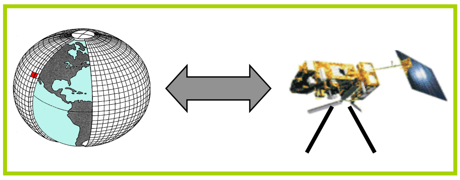
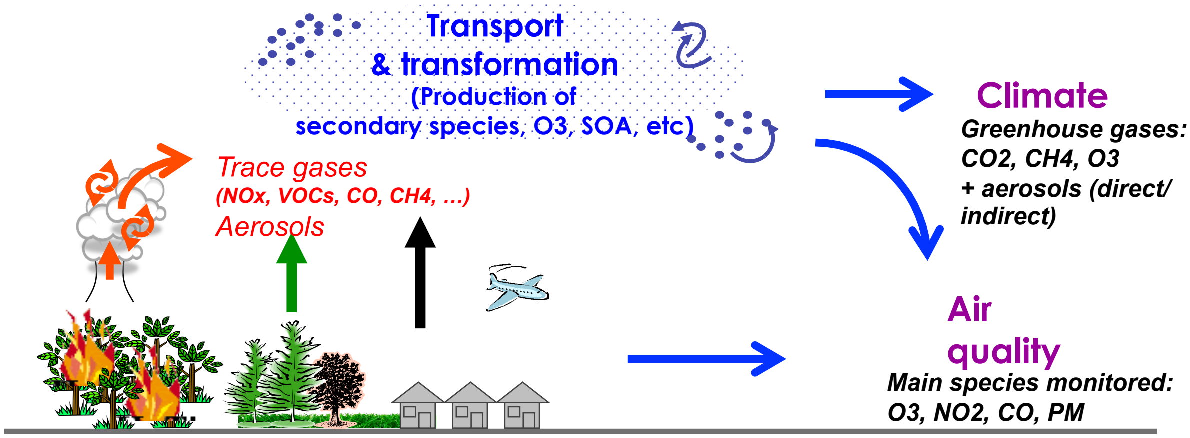
Understanding tropospheric composition

=> Analysis of observations and chemistry-transport model (CTM) simulations

- **Understand past air pollution events**
  - **➔ air quality**
- **Understand interannual variability and trends**
  - **➔ chemistry-climate interactions**



Key questions at different levels: emissions, transport, impact



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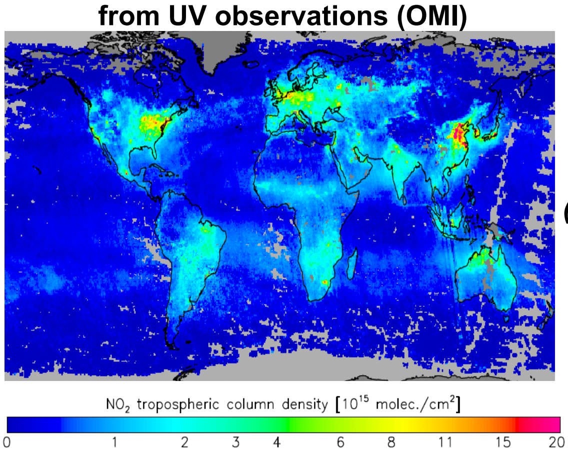
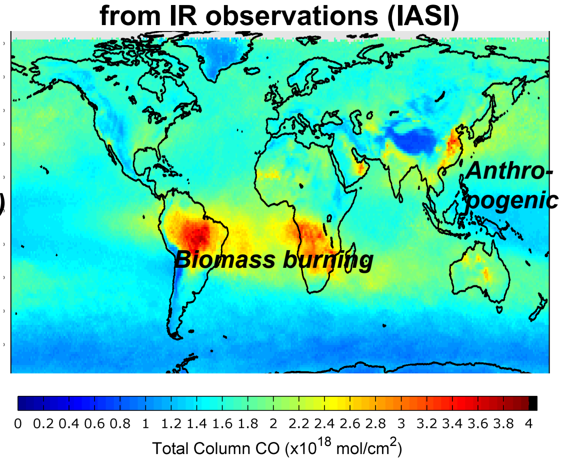
A few examples

Tropospheric NO2 *retrieval* from UV observations (OMI)



(October)

Total CO *retrieval* from IR observations (IASI)



Courtesy Folkert Boersma (KNMI)

Courtesy C. Clerbaux (LATMOS/IPSL, ULB)

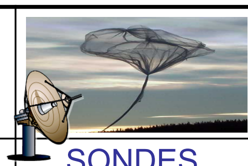
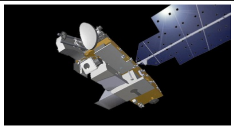
⇩

NO2 has short lifetime (hours to days)
~ direct information on NOx emissions

⇩

CO has relatively long lifetime (weeks)
Direct information on pollution transport;
BUT need chemistry-transport model to infer information on emissions ("inverse modeling")

Complementary observation strategies

	 SURFACE IN SITU	 SONDES, SURF.-BASED REMOTE	 AIRCRAFT	 SATELLITES
Horizontal coverage	-	-	+	+
Vertical range	-	+	~ (up to ~20 km)	~ (**often integrated**)
Vertical resolution	none	+	+	-
Temporal coverage	+	+	-	~ (polar = twice daily)
Chemical detail	+	-	+	-
Cost	+	+	~	-

(Adapted from C. Heald, U. Colorado)

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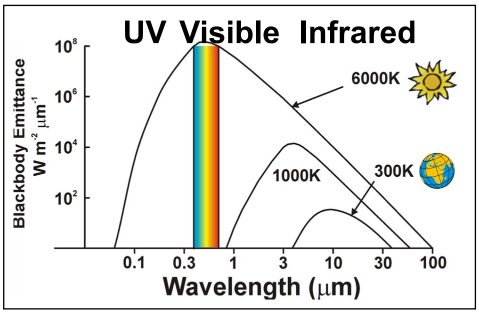
Passive remote sensing from space

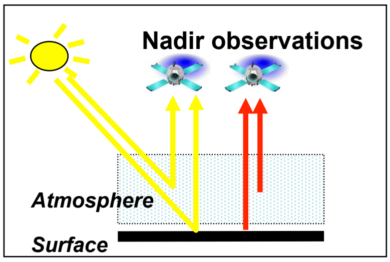
The Sun and the Earth-Atmosphere system emit radiation depending on their temperature (blackbodies)

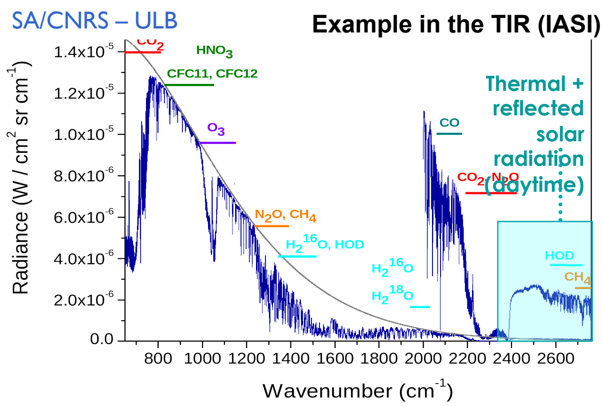


⇒ Interaction with the atmosphere depending on the wavelength: provides information on the composition of the atmosphere!

⇒ Radiative transfer is then used to «retrieve» atmospheric concentrations

=> This radiation can be measured by satellite-borne instruments

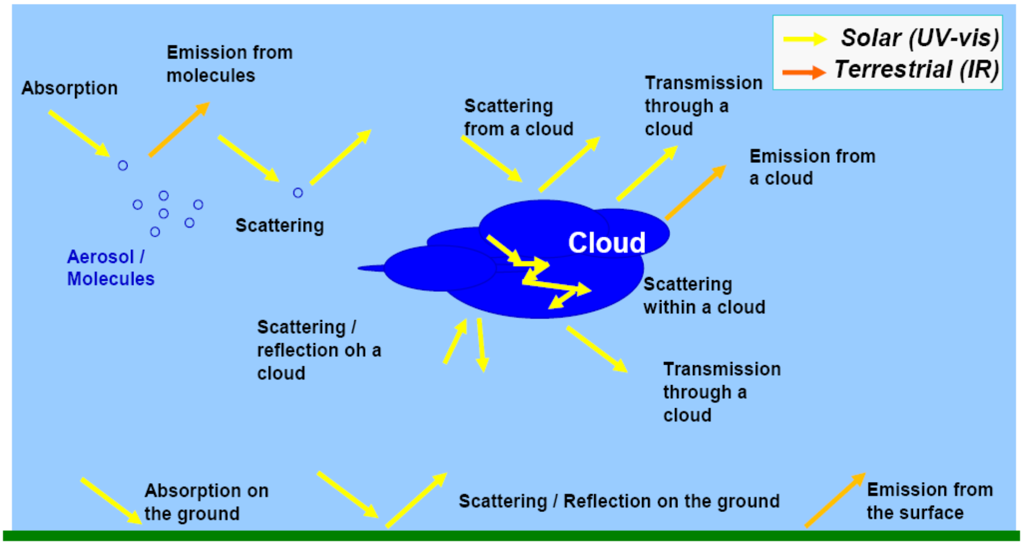




Radiative transfer: Interaction between radiation and atmospheric composition

Blackbody emission: $B_\lambda(T)$
"Greybody": account for surface emissivity => Radiance = $\varepsilon_\lambda \times B_\lambda(T)$ with $0 < \varepsilon_\lambda < 1$

Transmission through the atmosphere described by radiative transfer equations
Need to account for many interactions in the atmosphere!



Adapted from Andreas Richter, U. Bremen

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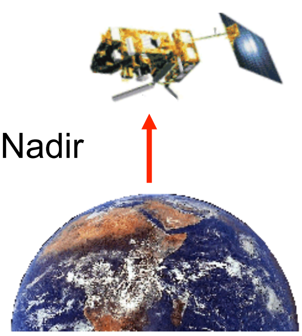
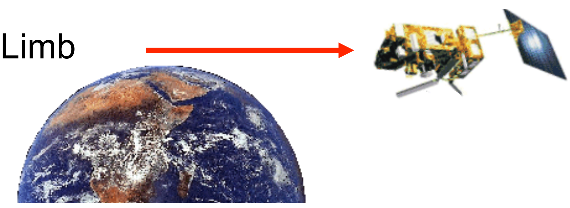
Geometry of observation: Different technique for different applications

Nadir



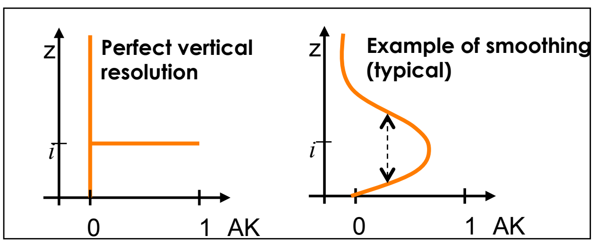
Limb



(+) vertical resolution (profiles)
(-) limited horizontal resolution
(+/-) upper troposphere and stratosphere

(+) horizontal resolution
(+) spatio-temporal coverage
(+) high sensitivity to the troposphere
(-) limited vertical resolution

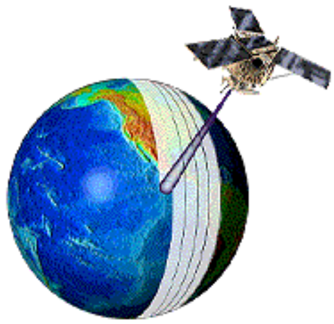
Occultation

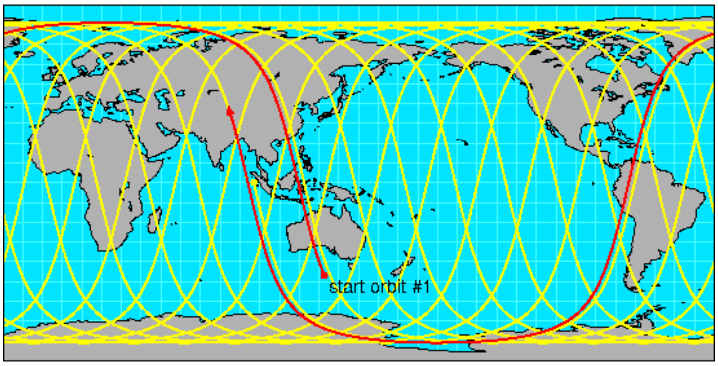


Polar orbit:

Low elevation (LOE) sun synchronous orbit (satellite precesses at same rate as Earth revolves around the Sun, ~1°/day)

➔ Keeps the same equator crossing time





- (+) Global coverage
- (+) High signal
- (-) Poor coverage (temporal, clouds)
- (-) Shorter instrument lifetime

BUT: instrument may scan across the satellite track to increase the coverage (off-nadir measurements)

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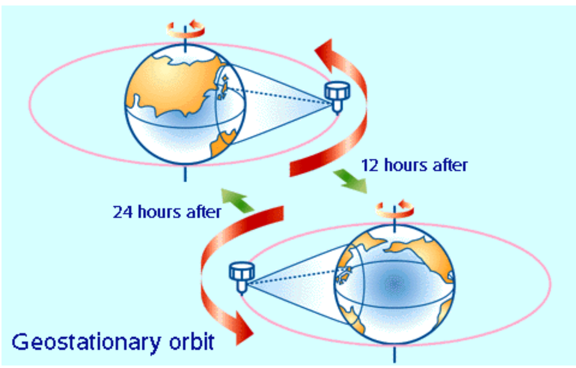
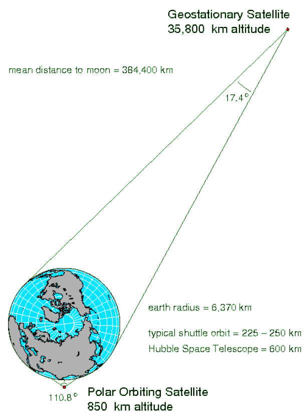
<u>Geostationary orbits</u> (GEO)

match the period of satellite rotation with the Earth's rotation (altitude ~ 35,800 km), fixed over the equator (view up to 60°)





- (+) constant observation (diurnal variation, cloud contamination less detrimental)
- (+) Longer instrument lifetime (less drag)
- (-) reduced signal
- (-) worse spatial resolution → limit of spatial resolution possible ~ 1km

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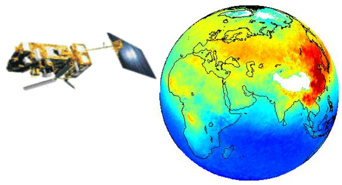
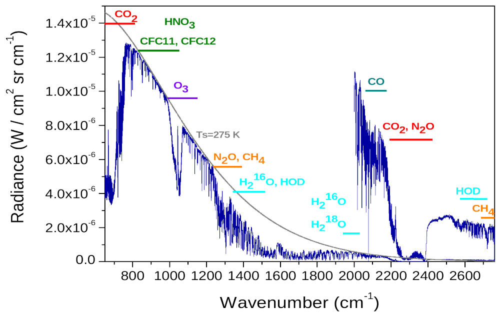
Using satellite observations: the inverse problem

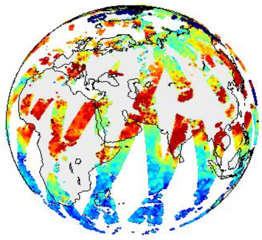


Level 1 observation



Inversion software

Level 2 product



[Users]

Often total column amounts (i.e. integrated concentrations)
Sometimes vertical profiles but with low resolution so unable to resolve fine structures

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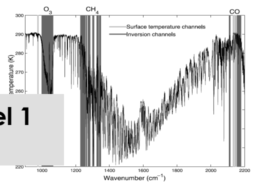
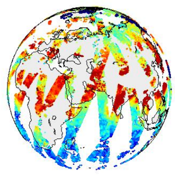
Generalization of the inverse problem

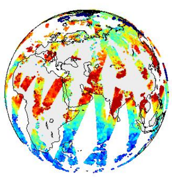
Level 1 obs.



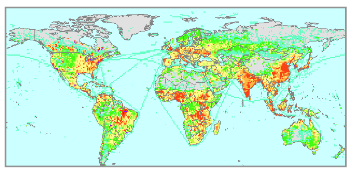
Retrieval of trace gaz concentrations



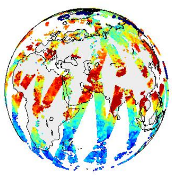
Retrieval Lev. 2



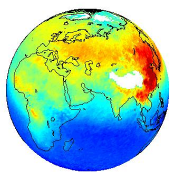
Inverse modeling of surface fluxes



Top-down Estimation



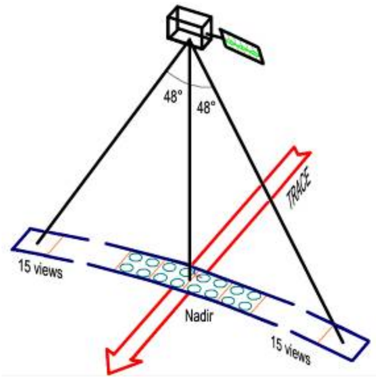
Data assimilation



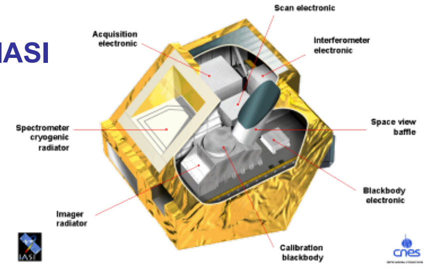
Level 3 distributions

Example of TIR observations: IASI/METOP (2006-…)

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES



IASI



- 12 km pixel x 4 @ nadir
- 120 spectra along the swath (±48.3° Scan →2400 km), each 50 km along the trace

Small ground pixel size => Detailed maps and increase the probability of cloud free obs.

Global coverage twice daily (morning and evening orbits)

- Spectral coverage = 645-2760 cm^{-1}
- Spectral resolution = 0.5 cm^{-1}
- Radiometric noise ~ <0.1-0.2 K

Broad spectral coverage without gaps => Signature from several species

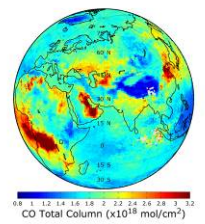
Medium spectral resolution

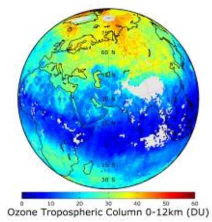
Large signal / noise

(adapted from Coheur et al., ULB)

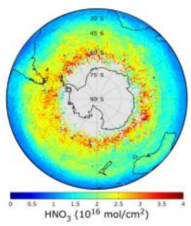
Average 1°x1°, 10 days, 18-28 August 2008

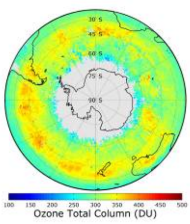
Pollution transport monitoring





Ozone hole formation and chemistry monitoring

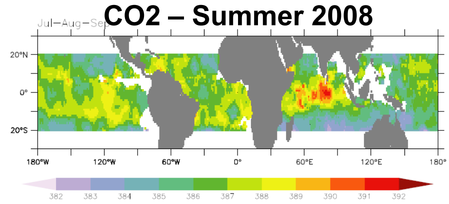




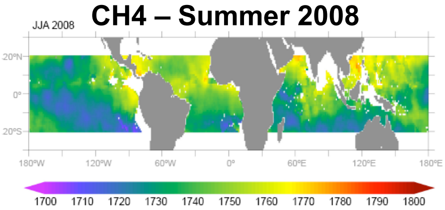
(Clerbaux et al., 2009, Atmos. Chem. Phys.)

Additional difficulty for long lived species : low variability requires very good accuracy of retrievals.

CO2 – Summer 2008



CH4 – Summer 2008



(Crevoisier et al., Atmos. Chem. Phys., 2009)

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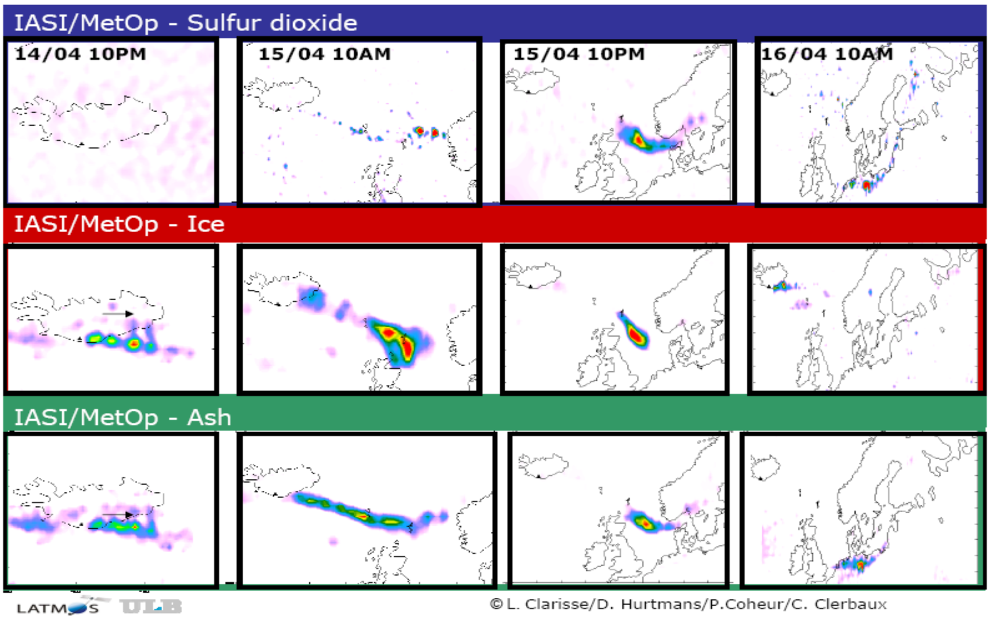
Examples of operational applications

- Following Volcanic plumes using IASI



- Assimilation of IASI observations at ECMWF (GEMS/MACC project)

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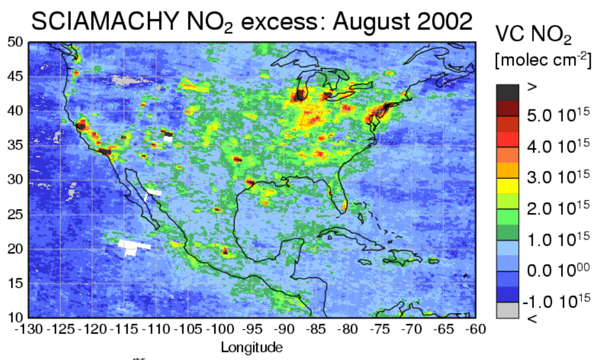
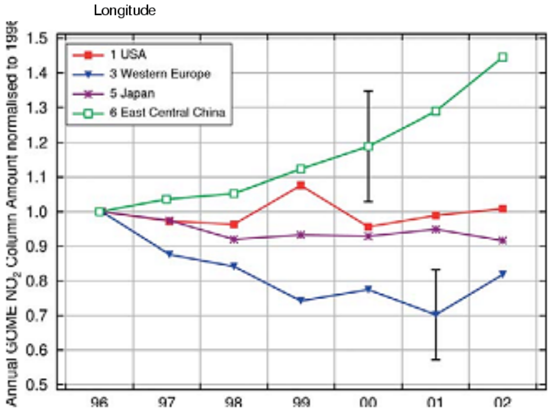
Importance of long term record: NO2 in UV-vis



Good horizontal resolution (i.e. detail)
& short-lived pollutant
=> Information on surface emissions



NO_2 emissions in US, EU and Japan decline …

while emissions growing in China

Importance of long-term record!

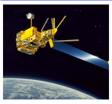
Richter et al., 2005; Fishman et al., 2008

Main missions for the observation of trace gases

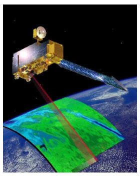
1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006

GOME/ERS-2

IMG/ADEOS

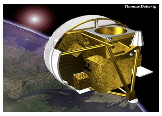


MOPITT/TERRA

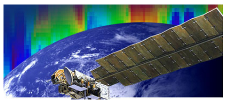


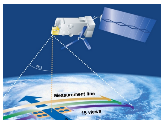
MIPAS/Envisat ; SCIAMACHY/ ENVISAT

ACE/SCISAT



TES, OMI/Aura

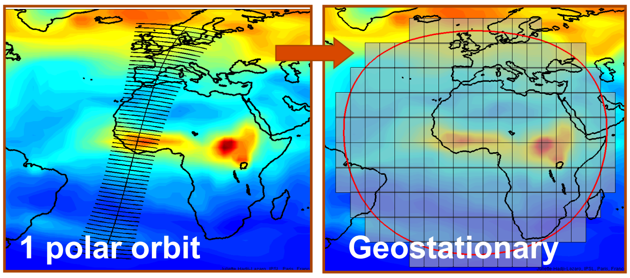




IASI/MetOp
GOME-2

Nadir viewing
Limb/Occultation
IR
UV

Future missions: towards geostationary observations



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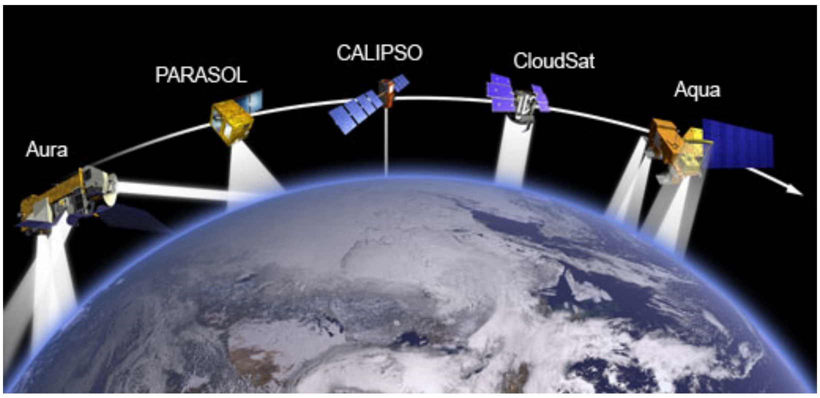
Train of satellites for near coincident observations



Aerosol measurements:
Aqua-MODIS
PARASOL
CALIPSO
Aura-OMI

Trace gas measurements:
Aqua-MOPITT (IR)
Aura-OMI (UV-vis)
Aura-TES (IR)

Three years of coincident aerosol measurements from launch of CALIPSO (Apr 2006) to de-orbit of PARASOL (Dec 2009)

A geostationary network for the future?

GEO-CAPE
NASA: 2016?

Sentinel-4/5
ESA: 2017

GEO-Asia
JAXA: 2017?

All three likely to include composition measurements in both UV & IR

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Further reading…

• Atmospheric radiative transfer, J. Lenoble, 1993.

• Inverse methods for atmospheric sounding, C. D. Rodgers (World Scientific Publishing Co Pte Ltd, 2000).

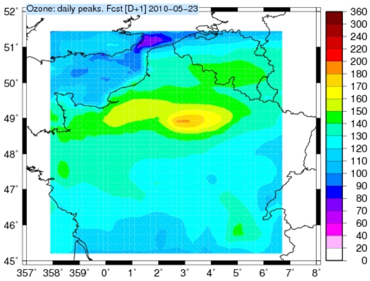
• Introduction to atmospheric chemistry, D. J. Jacob (Princeton University Press, 1999) ; electronic version available on the Pr Jacob web page at Harvard.

• IASI mission: recent special issue on first scientific results in the journal Atmospheric Chemistry and Physics (free online access: http://www.atmospheric-chemistry-and-physics.net/index.html)

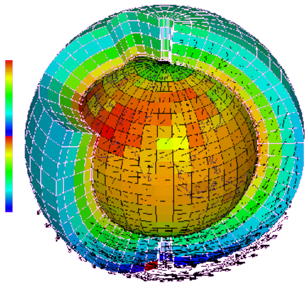
Numerical modelling of the atmosphere

Lecture by Thomas Dubos
Laboratoire de Météorologie Dynamique
Institut Pierre Simon Laplace

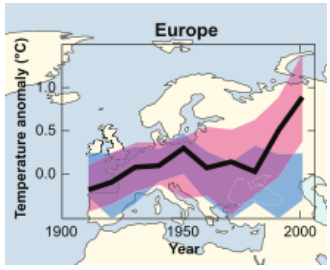
Applications



Basic principles

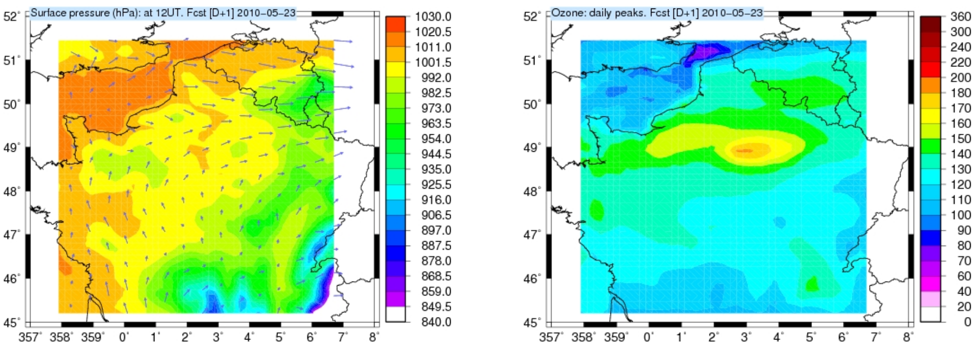


Sensitivity and validation



Weather and air quality forecasting

Provide in advance the value of temperature, rainfall, wind, ozone concentration ... at a given time and location



1-day forecast of surface pressure and ozone peak over Northern France

Requirements

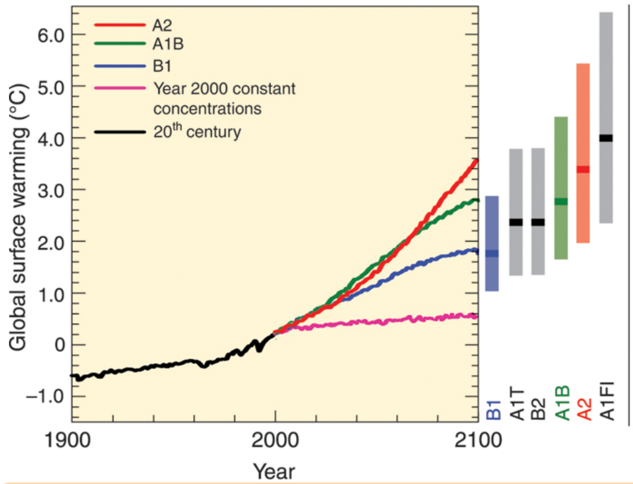
- Initial knowledge of the state of the atmosphere (wind, temperature, concentrations) *everywhere* including where no forecast is desired.
- Advance knowledge of forcings : radiation, emission of pollutants, ...

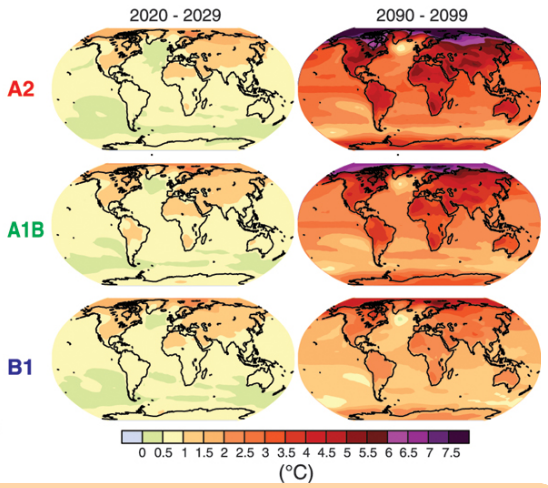
Applications

- Military
- Public safety
- Public health
- Aviation
- Agriculture

Projections of future climate

Investigate how climate (statistics of weather) is likely to change provided various scenarios of GHG emissions





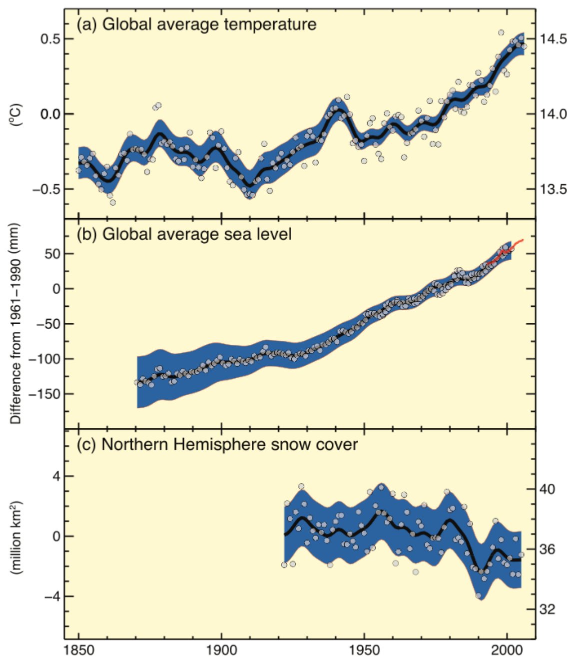
Sources of uncertainty (range of predictions)

- Natural variability — *irreducible*
- Discrepancy between models — *room for scientific improvement*
- Future emissions — *room for action*

Numerical modelling of the atmosphere
Applications of numerical models

Understanding causes and effects : numerical experiments

Reconstructed surface temperatures indicate a global warming during the XX^{th} century.



Is it ...

- A natural oscillation ?
- A naturally-forced (sun, ...) warming ?
- A human-caused long-term trend ?
- All of them ?

An answer requires

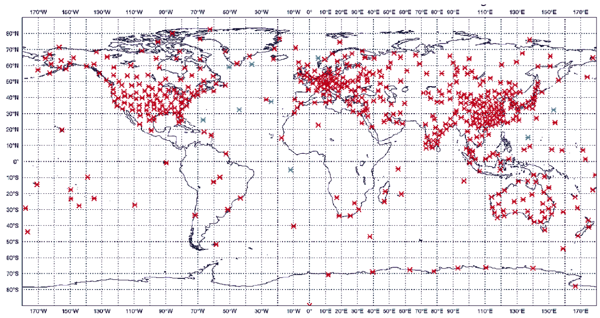
- Simulations with/without the physics suspectedly contributing to warming/ cooling
- Long/multiple simulations to span the variability of the climate system

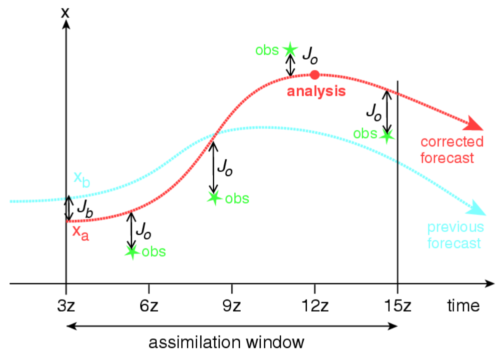
Reconstruct unavailable information : data assimilation

Estimate now the wind, temperature, ... everywhere provided scattered, and incomplete observations in the past

Principle

- Start with an estimate of the state of the atmosphere yesterday
- Run a simulation from yesterday until today
- Compute the difference between the simulation and the observations
- Update yesterday's estimate of the state the atmosphere to reduce the difference with observations
- Start over until statisfied



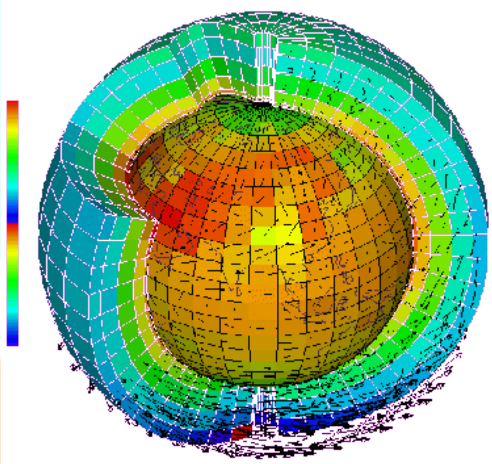


Fundamental budgets

Models divide the atmosphere in many cells and apply the fundamental laws of physics in each cell.

Example : mass budget

Cell ozone content now
= Cell ozone content XX minutes ago
+ Ozone transported by wind from adjacent cells
- Ozone transported by wind into adjacent cells
+/ Ozone produced/consumed by chemical reactions



Do the same with

- Other species
- Water (wapor, liquid, ice)
- Momentum
- Energy, entropy

Trade - offs

Discretization = expression of the laws of physics in a finite set of cells
Some laws can be exactly enforced (ex : total mass conservation ; positivity of concentrations) but most entail an approximation.

One must trade between resolution, accuracy, exact laws, simplicity, robustness ...
The most appropriate trade-off depends on the spatial and temporal scales of interest and the targeted application.

Application	Domain size	Resolution	Time scale
Global climate	40 000 km	100 km	A century
Regional climate	10 000 km	40 km	A few decades
Global weather	40 000 km	20 km	A week
Local air quality	1000 km	5 km	A few days

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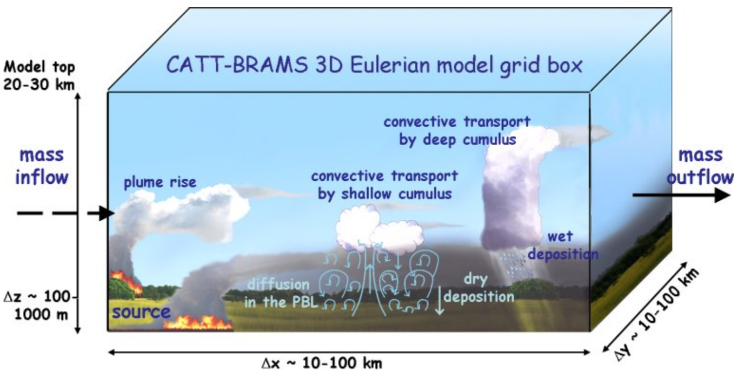
Numerical modelling of the atmosphere
Basic principles
Institut Pierre Simon Laplace — Sciences de l'environnement

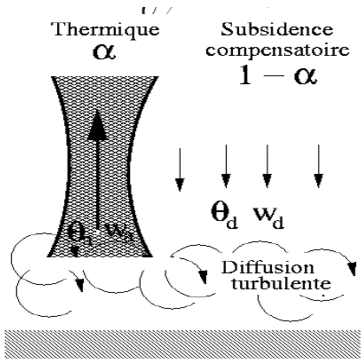
Physical parameterizations

Grid cell may be larger than certain objects/processes : individual clouds, water droplets, ...

These processes are unresolved.

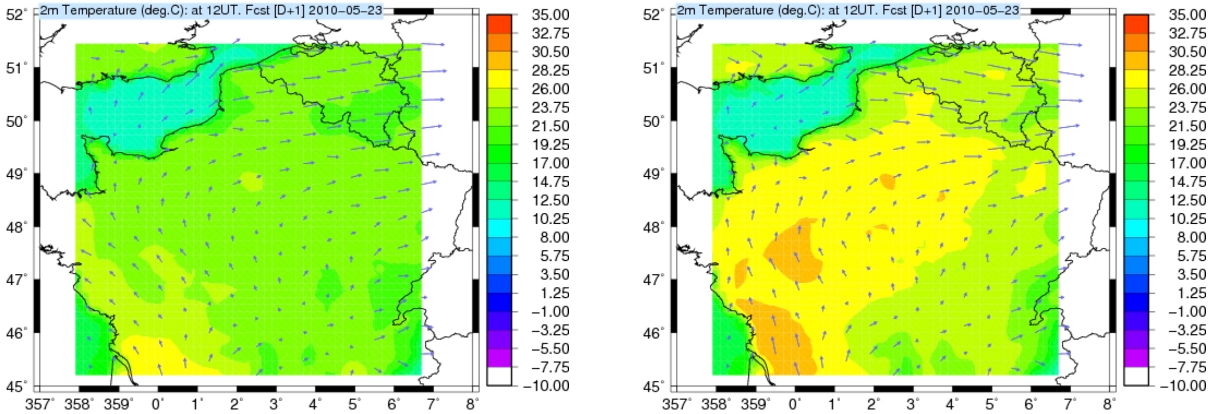
Their effect at the scale of the cell must be incorporated via physical parameterizations.





Sensitivity to physical parameterizations

For many small-scale processes more or less detailed descriptions can be adopted depending on the trade-offs that are most appropriate for a specific purpose. The impact on the modelled atmosphere can be significant.

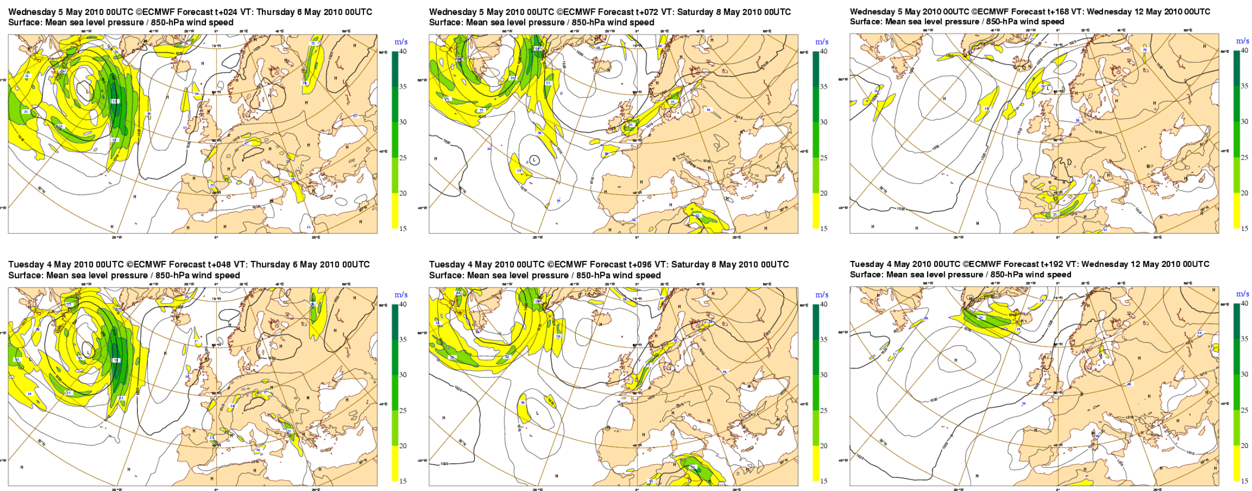


1-day weather forecasts of near-ground temperature differing only by how the surface hydrology is represented

Numerical modelling of the atmosphere
Model sensitivity and validation

Sensitivity to initial conditions

Two simulations initialized with slightly different initial conditions. Forecast 1, 3, 7 days in advance.



Exponentially growing difference between the two simulations : *chaos* or *butterfly effect*

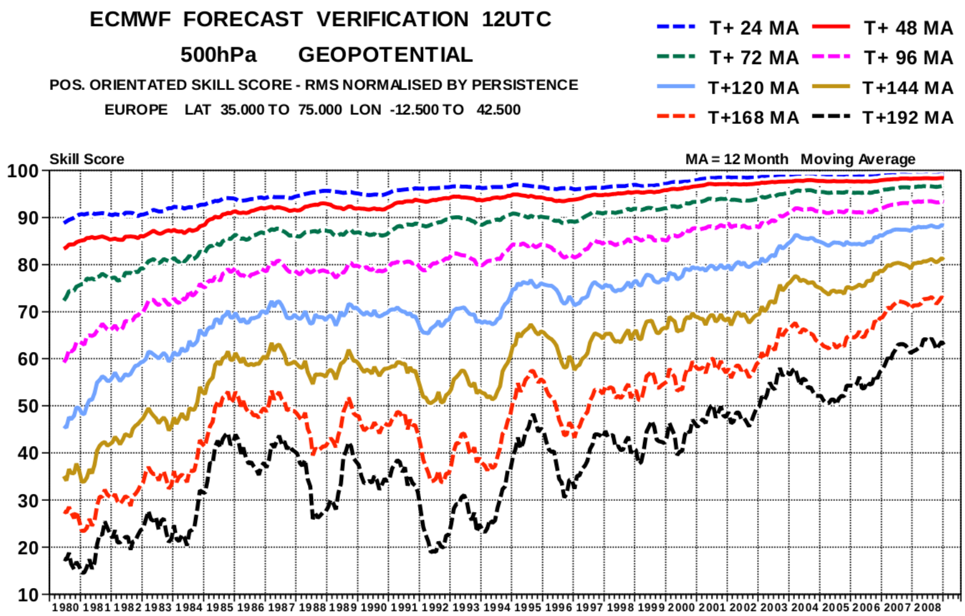
Small but inevitable errors in the initial conditions

⇨ useless weather forecast after a week or so (even with a perfect model)

This is an intrinsic property of the atmosphere (not due to model errors).

Deterministic validation (weather)

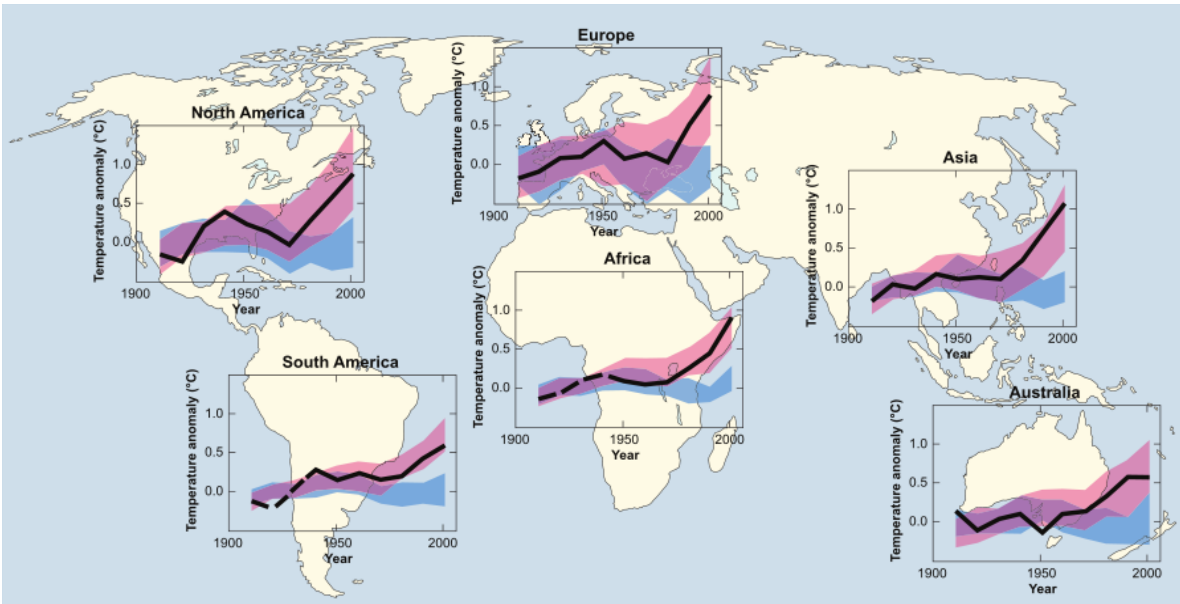
Deterministic validation is the process of checking that a model reproduces observations on a daily (or hourly, etc .) basis everywhere. The agreement between the model and observations can made quantitative by computing a score : relative root-mean-square deviation, correlation coefficient, ...



SIRTA
Numerical modelling of the atmosphere
Model sensitivity and validation
Sciences de l'environnement
Institut Pierre Simon Laplace

Statistical validation (climate)

Unlike weather forecast models, climate models are not reinitialized every day to match observations. Therefore they are not expected to reproduce observations on a daily basis, but to reproduce the statistical distribution of observations : decadal global mean, probability of events, ...



Numerical models used in climate sciences implement laws of physics

Only parts of the physics are resolved and discretized ; unresolved processes are parameterized

Deterministic models can make short-term deterministic forecasts or long-term statistical projections

Models are validated by comparing them to observations

Models can also be used to solve inverse problems

In the absence of experiments and pen-and-paper theory, only models can test hypotheses and identify causes

Numerical modelling of the atmosphere

Contributions by C. Basdevant, F. Hourdin and C. Rio (LMD)

Other sources :

- Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch)
- European Center for Medium-Range Weather Forecast (http://www.ecmwf.int/)
- COSY project (http://www.lmd.polytechnique.fr/cosy/cosy.php)
- PREVAIR project (http://www.prevair.org/fr/index.php)

SPATIAL AND TERRESTRIAL MONITORING OF ENVIRONMENT AND NUMERICAL SIMULATIONS

— Practical Classes —
Measuring atmospheric particles with SIRTA lidars

Albert Hertzog (hertzog@lmd.polytechnique.fr)

1) Objectives

The objectives of the Lidar practical activity are the following:
- to understand the measurement principle behind backscattering lidar observations
- to learn the various components of a lidar system, and to be able to make a data acquisition on such a system
- to understand how the analysis of lidar observations is performed
- to retrieve information on cloud and aerosol layers in the atmosphere on a case study with lidar and correlative radiosounding observations

2) Schedule

The activity is divided into several workshops. After the morning general introduction, the students are directed to the "LNA" (French acronym for Cloud and Aerosol Lidar) building. The visit of the facility is used to describe in further details the various subsystems of a backscattering lidar. Direct observations of the current measurements are proposed on an oscilloscope plugged on the photons detectors. The students are encouraged to start a data acquisition sequence and to modify defaults parameters to optimise the observations.
In the afternoon, the lidar observations are analysed on computers. The various structures that appear on the datasets will be interpreted and will emphasize the capabilities of lidar systems. They will also serve to exemplify the atmospheric structure or geophysical processes (troposphere/stratosphere, boundary layer and its diurnal cycle, phase transition in clouds, particle sedimentation, etc.) Finally, lidar observations will be compared with in-situ measurements from a radiosounding profile performed in a nearby location.
The second part of the afternoon is devoted to the drafting of the student report. It will be the opportunity to organise and synthesise the information that have been collected during the day, and to clearly illustrate, on a case study, how lidar systems can contribute to improve our knowledge of the atmospheric environment. The report will also be the occasion to further think on the applications of such remote sensing system besides atmospheric research.

3) Practical considerations

Details of the LNA lidar are given in an appendix to this document.
Lidar observations are analysed with a devoted software called "vl2", which is launched by typing "vl2" in a terminal window. vl2 displays the number of photons (corrected from noise and, if selected, from geometrical effects) with colours, versus time (x-axis), and altitude (y-axis). It also allows the user to select which channel is displayed (532 nm parallel- or perpendicular-polarization, 1064 nm), to modify the axis ranges or the color scales, to do some temporal or vertical averaging, and to analyse the depolarization of the backscattered signal. The views produced can be printed by a printer or saved as files for the report. A snapshot of vl2 screen and main menus is shown below (Fig. 1).

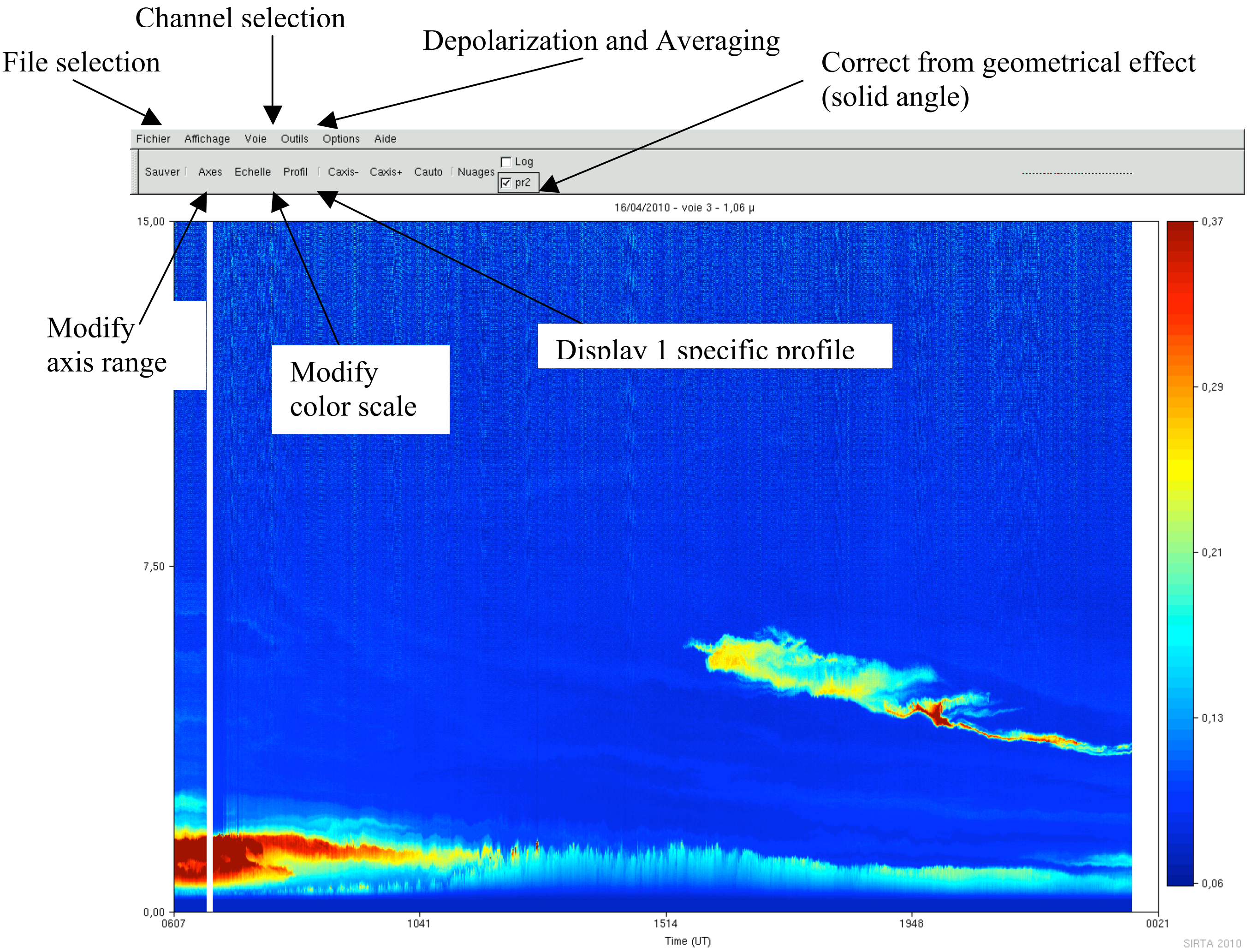


Figure 1 : a snapshot of vl2 graphical interface

The radiosounding dataset is analysed with Matlab, a general-purpose scientific software. Matlab is launched by typing "matlab" in a terminal. The syntax of main Matlab commands is:

- load a data file: **mat=load('file_name');** As a result, the data matrix is stored into the **mat** variable in matlab environment
- plot a curve: **plot(mat(:,2),mat(:,1),'r');** This command plots the first column of **mat** (y-axis) vs the second one (x-axis). The last argument of **plot** (optional) indicates that the curve should be plotted in red.
- change axis ranges: **axis([xmin, xmax, ymin, ymax]);**
- change axis labels: **xlabel('my label for x_axis');** Alternatively, one can use **ylabel**.
- Change plot title: **title('my title');**

The produced graphics can also be printed or saved as files for future use.

4) <u>Questions</u>

The following questions can be used to guide the report. The answers to these questions should be (as much as possible) illustrated with figures produced by the students during the case-study workshop.

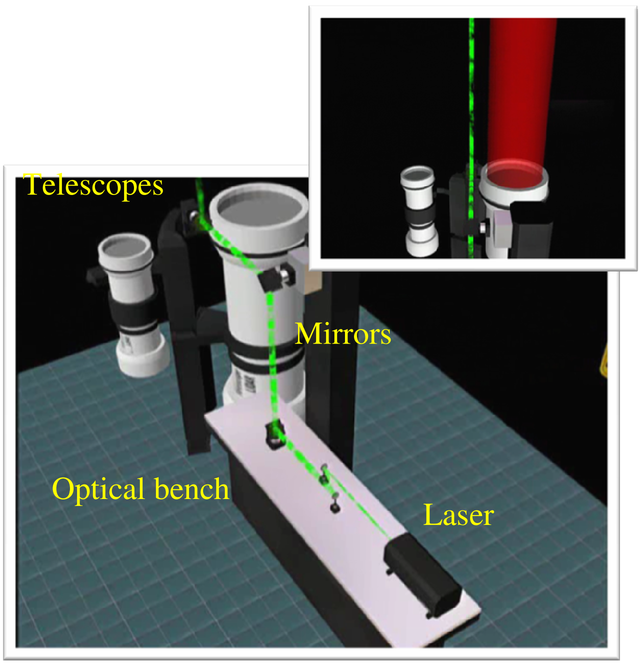
- Describe in a broad way how an active remote sensing system is working (Illustrate the main functionalities with radar or lidar). What are the principal parameters that have to be chosen during the design of a new instrument ?
- How are clouds and aerosols measured with the backscattering lidar that you used today ?
- Which information on clouds and aerosols could you infer from lidar and radiosounding observations ?
- How would you improve the existing backscattering lidar ?
- Can you imagine applications of lidar technology out of the atmospheric research domain ?
- After joining with the other subgroups, could you elaborate on the relative merits and deficiencies of ground-based and space-borne observations ? and numerical simulations ?

Clouds and Aerosols LIDAR (LIght Detection And Ranging)
– Practical Classes –

LIDAR, like RADAR, are based on interactions between electromagnetic waves and matter. RADAR use millimeter electromagnetic waves emitters while LIDAR use light as source.
Nonetheless while the first RADAR was developed in 1935, the first LIDAR system was developed in 1962 to measure echo from the lunar surface. The first observations of the troposphere turbidity by LIDAR did not start before 1964.

Multiple progresses in laser sources, optics and fast response electronic did enhance performances of LIDAR systems. Now, new industrial design make LIDAR systems more compact and portable.
The Laboratoire de Météorologie Dynamique (LMD) developed many lidar systems since its creation in 1968 and still develops new systems dedicated to ground and airborne observations or dedicated to space platform.

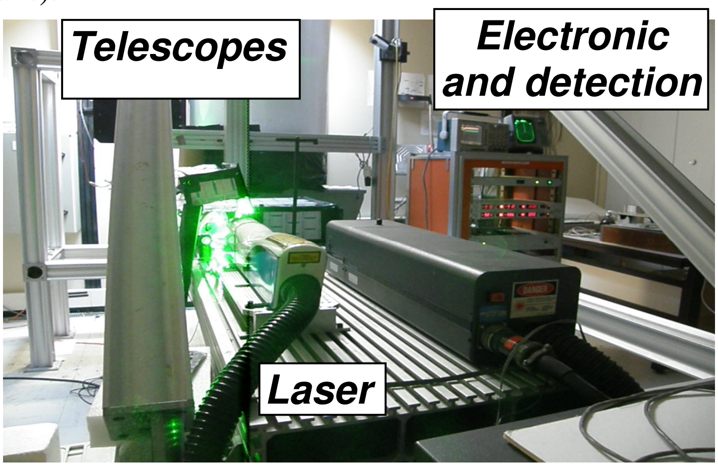
The SIRTA (Site Instrumental de Recherches par Télédétection Atmosphérique) observatory takes advantage since 1999 of the clouds and aerosols LIDAR (LNA) system developed by LMD to monitor the processes in the troposphere.

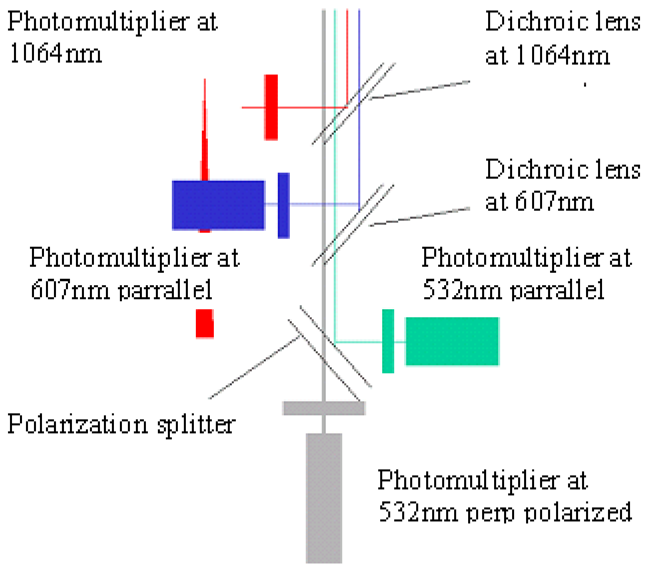


LNA lidar is composed of a pulsed laser Nd-YAG (Yttrium-Aluminum-Grenat doped with Néodyne) operating at 1064nm, doubled at 532nm and linearly polarized. A beam expander is used to increase the beam diameter and to reduce its divergence. The backscattered signals resulting of interactions with molecules and particles in the atmosphere are collected by two telescopes, which one is characterized by a narrow field of view (NFOV), and the second one by a wide field of view (WFOV). The NFOV telescope is devoted to detect interactions that occurred in the high atmospheric layers (2-15 km), while the WFOV telescope is dedicated to explore the low atmospheric layers (0.1-7km).

The backscattering lidar principle is based on a laser pulse emitted in the atmospher. The laser pulse propagating through the atmosphere is diffused by molecules, aerosols, water droplets and ice crystals. The scattered light is partly backscattered down to the optical system more or less intense depending of the emitted wavelength, the particle concentration, size and shape. The backscattered light is collected through the telescope connected to an analog photo multiplier detector that converts the incident energy to electric signal. The signal is then digitalized to numerical counts using a PC equipped with acquisition cards and recorded before processing.
Time for the backscattered light to travel at light speed is converted to distance. The pulse propagates through a distance ct/2. Acquisition cards operate at 10MHz sampled frequency to allow 2000 records and to allow exploring the atmospheric path up to 30km with a vertical resolution of 15m.

The laser beam must entirely cover the field of view of the telescope to allow retrieving the entire backscattering signal. The laser beam located between the two telescope and having a divergence of 0.6 milliradians imply that full cover is reached at about 2 km for the NFOV telescope (FOV=1.6 milliradians) and a few hundred meters for the WFOV telescope (FOV=11 milliradians).





Combining the signals from the two telescopes allows exploiting entirely the measurements along the atmospheric path between grounds up to 15 kilometers.
Each telescope is coupled to a detection system composed of many optical components designed to separate and measure the signals at 1064nm and 532nm. The optical system is designed also to detect the signal linearly polarized and the depolarized signal at 532nm.

Quicklooks are created in real time and are accessible on the web http://sirta.ipsl.polytechnique.fr (data tab).
Data are processed and are accessible 24 hours after acquisition in the SIRTA database.

Clouds and aerosols Lidar characteristics:

- light source: Nd:YAG pulsed laser
    i. emitted wavelengths: 1064 nm and 532 nm (thanks to a KDP crystal)
    ii. pulse frequency: 20 Hz
    iii. shot duration: 10 ns
- narrow-field telescope:
    i. type: Cassegrain
    ii. diameter: 60 cm
    iii. altitude of field total overlapping: 2 km
- reception channels:
    i. 1064 nm
    ii. 532 nm with polarization parallel to the emitted beam
    iii. 532 nm with polarization perpendicular to the emitted beam
- data acquisition:
    i. temporal gates: 0,1 µs
    ii. number of gates: 1024
    iii. resolution: 12 bits

SPATIAL AND TERRESTRIAL MONITORING OF ENVIRONMENT
AND NUMERICAL SIMULATIONS

– PRACTICAL CLASSES –

SATELLITE OBSERVATIONS FOR ATMOSPHERIC POLLUTION MONITORING

by S. Turquety

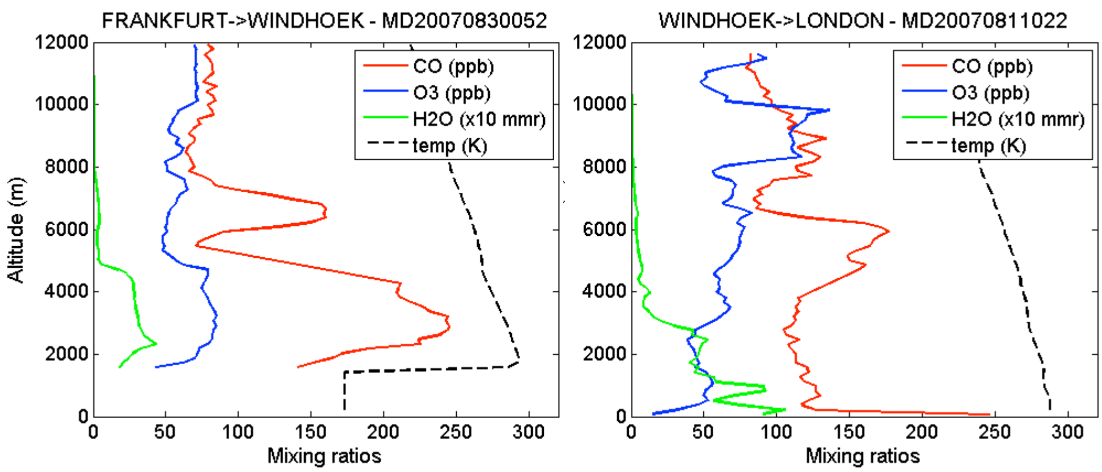
I. Introduction

Satellite measurements allow the monitoring of a wide number of atmospheric species. In passive remote sensing, the radiation emitted by the Sun or the Earth's surface (and, to a lesser extent, its atmosphere) is measured by a satellite-borne instrument. As it crosses the atmosphere, the radiation is modified through interactions with atmospheric constituents: clouds but also particles and molecules. Their scattering and/or absorbing properties depend on the frequency[1], so that specific spectral regions[2] provide information on specific species (cf. lecture). Some instruments are able to measure a detailed spectrum, i.e. the radiation decomposed as a function of the frequency (or wavelength) with a small resolution (interval between two recorded frequencies). Numerical tools based on physical properties and statistical estimation are developed in several research and operational application to retrieve atmospheric composition from these recorded spectra.

Here, we will analyze spectra in the thermal infrared (TIR) for the observation of carbon monoxide (CO), a species observed since more than a decade by various missions. CO is a tracer of pollution transport: emitted by anthropogenic activities and biomass burning, it can then be transported on thousands of kilometer. Satellite observations of CO have provided a first testimony of the importance of trans-boundary pollution.

II. Simulation of satellite observations

The objective of this first part is to simulate observations from recent atmospheric sounders measuring in the TIR (spectra), and highlight the main signatures from influencing species. Therefore, a numerical program simulating the interaction between emitted radiation and the atmosphere (a radiative transfer code) is used. Here, we will use the *Atmosphit* software, developed at Université Libre de Bruxelles (ULB) in collaboration with LATMOS/IPSL.



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[1] Frequency (ν), wavelength (λ) and wavenumber ($\bar{\nu}$) all indicate a given spectral region, and are linked by : $\bar{\nu} = 1/\lambda = \nu/c$ with c the celerity of the radiation.

[2] Remember that the spectrum of light goes from the ultraviolet (UV 10nm<λ<300nm)) to the visible (violet to red) and the infrared (IR 1μ m<λ<500μm)

Figure 1 - Vertical profiles of temperature, water vapor, carbon monoxide (CO) and ozone (O3) observed above Windhoek (left) and London (right) during descent of MOZAIC aircraft.

Satellite observations will be simulated for two example sites: London (UK) and Windhoek (Namibia). These locations were chosen for the availability of *in situ* observations of atmospheric profiles for several key species from the MOZAIC commercial aircraft observation network (Figure 1, see Annex 1 for details). On your workspace, you will find several input directories corresponding to these examples and containing all input files needed for the numerical simulations *with the Atmosphit software* (cf. Annex 2).

II.1 Simulation of atmospheric radiation measured from space

In this first part, we will calculate the radiance spectrum (so-called "forward" simulation) as it would be observed from space by two instruments launched in the recent years with different spectral resolutions (i.e. accuracies): TES launched on board the AURA satellite in 2004 and IASI launched on board the METOP satellite in 2006 (cf. Annex 1).

Table 1 – Approximate spectral resolution for different missions.
The spectral range is chosen to range from 645.0 cm^{-1} to 2760 cm^{-1} (IASI instrument).

Instrument / Platform	IASI/METOP	TES/AURA
Sampling resolution (cm^{-1})	0.25	0.05

a) Simulation of IASI observations above London.

1) Launch Atmosphit (shortcut on your desktop) and remove ascii output option (not used here) in the run menu;

2) Open the "London_IASI_forward" directory containing the input files necessary for the numerical simulation; Use your mouse to "drag and drop" each input file to the software window (HITRAN, BMD, FIN and spectrum files, cf. Annex 2 for detail);

3) Compute the corresponding spectrum using: Run > compute > spectrum. Once the run is completed, the computed spectrum is plotted on the "spectrum" window, and a matlab file is created, containing the simulation output.

4) Plot the simulated observation using the matlab function visu_spectrum.m (provided in your work directory): open the matlab software and write the following command:

[w,rad,rad_noisy]=visu_spectrum_fwd('yourspectrum.mat','london_iasi',1)

Where w is the wavenumber, rad is the simulated measured radiance, and rad_noisy is the radiance after adding noise (cf. part 1.2).

b) Use the same procedure to simulate TES observations above London (using the corresponding input directory "London_TES_forward". Compare both spectra;

c) For the TES configuration, you will find additional input files in the directory, containing the atmospheric conditions (BMD file) but with one of the species set to zero. How may these cases be useful to isolate the spectral signatures from several absorbing species: H2O, CO2, O3, CO and N2O? Perform this sensitivity analysis. What spectral range seems best suited for the observation of CO concentrations?

d) Use procedure a1-a4 to perform simulations for both observation sites with IASI and TES instrumental characteristics, using the corresponding input directories. Check your results and archive (i.e. copy) the output matlab files in a new directory (e.g. RESULTS_FORWARD).

II.2 Accounting for random instrumental noise

In order to simulate realistic measurements, a random noise is applied to the spectra simulated in the first experiment. The matlab function visu_spectrum.m created new output files corresponding to the simulation plus a random noise, taking the IASI levels in the CO region. An excel file is created containing the noisy spectrum (file with extension .noisy.csv). Add these noisy observation files to the results archive. It is these files that will be used in the following for the retrieval experiments.

III. Carbon monoxide (CO) retrieval experiments

Each of the simulated spectra will now be used in CO retrieval experiments in order to check the capabilities of our simulated instrument to observe distributions of CO. The *Atmosphit* software will now be used in "inverse" mode.

III.1 Retrieval using optimal estimation

a) Perform a retrieval of CO above London from the IASI and TES simulated observations (including noise) using the following procedure:

1) In the CO retrieval directory, the input files needed for the inversion are provided for the different examples. Drap and drop the files for London and each instrument to the *Atmosphit* software window: BMD and FIN files and the HITRAN database, as well as the spectrum to be inverted (from your RESULT_FORWARD directory).

2) Launch the inversion using: Run > Fit spectrum > Optimal estimation. Once the inversion is completed, a matlab file is created in the work directory containing the inversion results. Copy the file to an archive result directory.

3) Use the function visu_inversion.m in matlab to plot the shape of the inverted profile and corresponding characteristics.

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visu_inversion('filename.mat')
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Compare the retrieved CO profile to the in situ observations of Figure 1. Discuss the potential improvements allowed by a finer spectral resolution.

b) Same exercise at Windhoek site.

III.2 Analysis of the characteristics

The averaging kernels profiles are one of the characteristics plotted by the visu_inversion function. It is commonly used for the characterization of the ability of the satellite to resolve a vertical profile. The number of independent information on the vertical is derived from these kernels as well as the vertical resolution for each simulation (full width at half maximum).

a) Discuss these characteristics for each of the experiments undertaken.

b) If time allows, conduct a final experiment by scaling down the noise level for one of the above experiment.

c) Summarize your results in a table and discuss the importance of spectral resolution for the retrieval. What additional uncertainties may affect the measurements in "real" conditions?

IV. Analysis guidelines (for restitution presentation)

Question 1 - Results of the Observing System Simulation Experiment

This practical class is a first step of an "Observing System Simulation Experiment" (OSSE). Explain what species may be observed in the TIR and for what possible application. Detail what needs to be characterized and how this kind of study may help define future missions.

Question 2 - From simulation to reality

Maps and profiles of CO retrievals using an algorithm similar to *Atmosphit* but optimized for IASI are provided in the "IASI" directory on your workspace (you can also browse maps on the IASI visualization page at LATMOS www.iasi-chem.aero.jussieu.fr). From the comparisons undertaken in part 2.3 and from the maps available online, discuss why working on real measurements to analyze the capabilities of future missions may be more useful.

Question 3 - Operational use of satellite observations

Satellite observations of atmospheric composition may be used for several operational applications. Give a few examples. What are the key elements to account for when using these data?

Question 4 - What future mission for trace gases?

Future missions are often a trade-off between instrumental characteristics. Why? What would be a perfect mission for air quality monitoring? For climate gases?

Annex 1 – Description of observations

MOZAIC program

The Measurements of OZone, water vapour, carbon monoxide and nitrogen oxides by in-service AIrbus airCraft (MOZAIC) program was initiated in 1993 by European scientists, aircraft manufacturers and airlines to better understand the natural variability of the chemical composition of the atmosphere. It consists of automatic measurements of reactive gases on board long range passenger airliners. Until 2009, MOZAIC was co-funded by the European Commission, national institutes (INSU-CNRS, FZJ, Météo-France, University of Cambridge) and supported by airlines (Lufthansa, Air France, ex-Sabena, Austrian). Its extension to the IAGOS-ERI database is cofunded by ETHER (Thematic Assembly Center, CNES and INSU-CNRS). *More info : http://mozaic.aero.obs-mip.fr/web/*

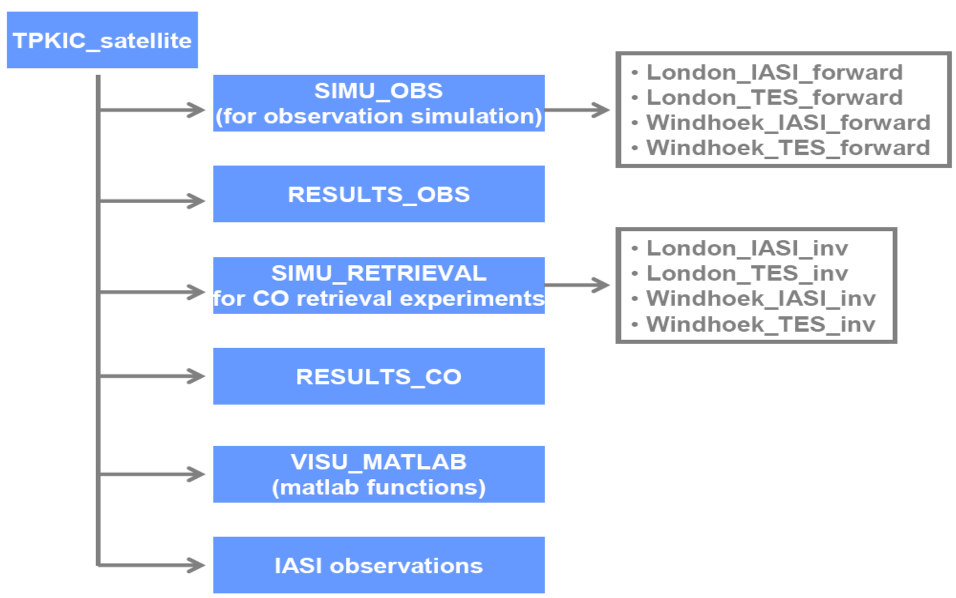
TES/AURA mission

The Tropospheric Emission Spectrometer (TES) is a NASA instrument is a high resolution Fourier transform spectrometer that was launched on the Aura spacecraft on 15 July 2004. It measures thermal emission from the Earth-Atmosphere system in both nadir and limb modes (Beer et al., 2001). The satellite is in a sun-synchronous orbit and the horizontal resolution of the nadir observations is 8 km×5 km. The IR spectra are recorded with a very high spectral resolution, allowing the retrieval of trace gas profiles for several species, in particular ozone and carbon monoxide (CO). More info: *http://tes.jpl.nasa.gov*.

IASI/METOP mission

The Infrared Atmospheric Sounding Instrument (IASI) was designed by the French space agency CNES and is operated by EUMETSAT. It was launched in December 2006 on board the European sun-synchronous satellite METOP. Like TES, IASI is a Fourier Transform Spectrometer recording IR spectra with a good spectral resolution. Combined with a low radiometric noise, it allows the retrieval of a series of IR absorbing species. In addition to nadir observations, its large swath across nadir (120 spectra are recorded along each swath) allows global coverage twice daily, with a small field of view of 2×2 circular pixels, each of 12 km footprint diameter at nadir. More info: *http://smsc.cnes.fr/IASI/*.

Annexe 2 – Schematic view of work directory



ANNEX 3 – ATMOSPHIT SOFTWARE INPUT FILES

File type	Extension	Purpose	Information provided
HITRAN	.hit	Spectroscopy	Absorption lines for all species reported in laboratory experiments;
BMD	.bmd	Atmospheric conditions	Profiles of pressure, temperature, water vapor, and absorbing molecules; A priori information in the case of an inversion;
FIN	.fin	Instrumental characteristics and inversion specifications	All information on: o Instrumental geometry o Instrumental spectral resolution o Inversion specifications
Spectrum	.csv	Spectrum	Wavenumber and corresponding radiances sampled on the instrument spectral resolution; Radiance equal to the observation or to zero for a simulation of the spectrum (i.e. provides only wavenumber and resolution information).

SPATIAL AND TERRESTRIAL MONITORING OF ENVIRONMENT AND NUMERICAL SIMULATIONS

- Practical Classes –
Numerical modelling

Thomas Dubos dubos@lmd.polytechnique.fr
Dmitry Khvorostiyanov Dmitry.Khvorostiyanov@lmd.polytechnique.fr

This practical class on numerical modelling is divided into two themes: model sensitivity and model skill. You will work on one theme for two hours in the morning. After lunch, you can choose to work two hours on the other theme, or to continue with your morning theme. The proposed work consists mainly of analyzing and comparing datasets that we provide to you. The analysis is performed in the Matlab environment using a small number of routines also provided to you. The routines draw plots which can be saved and imported into your presentation/report.

Theme 1 : Model sensitivity

Model sensitivity is the dependence of model outputs to changes in the information which is "fed into" the model. This includes the physical content of the model itself, but also the initial condition used to compute a weather forecast. There is also a sensitivity to information provided at the boundaries of the computational domain. This includes the lower boundary (exchanges of heat, water, etc. with the ground) and lateral boundaries if the computation is not performed over the whole globe, which is the case for many high-resolution applications such as air quality forecasting.

You are provided with the values, during two selected days, of surface temperature, rainfall, cloud cover, surface ozone concentration from the following sources :

- measurements performed at the SIRTA site
- air quality forecasts produced by the chemistry-transport CHIMERE model over France. For this practical class, air quality is forecast 6 days in advance. Therefore for the same day 6 forecasts are available depending how far in the past the forecast was made.
- air quality forecasts produced by the chemistry-transport CHIMERE model using "real" winds, i.e. the chemistry is forecast but the winds are obtained from reanalyses computed a posteriori to match observed winds as closely as possible.

Work :

1. *Sensitivity to initial conditions*

Plot maps of temperature and rainfall for two forecasts initialized at different dates. Observe the amplification with time of differences in initial conditions.

2. *Sensitivity to physical processes*

Plot the evolution of the forecast quantities. Compare to the observed time series. Was the forecast more successful on one of the two days ? Find important differences in the

meteorological situation of the two days. Are the associated physical phenomena explicitly resolved in the model, or are they parameterized ?

3. *Sensitivity of chemistry to model winds*

Compare the forecast of ozone concentration when using either forecast winds or analyzed winds. Comment on the observed differences in terms of sensitivity of an air quality model to winds, to initial concentrations of chemical species and to sources/sinks of chemical species.

We encourage you to address the following questions in your report:

- What information does an air quality numerical model need in order to perform a forecast ?
- What is called sensitivity to initial conditions ? How large can grow discrepancies in temperature, rainfall, … after one day ? Several days ?

Theme 2 : Model skill

The skill of a numerical model can be evaluated by comparing it to observations, or to another model with a known high skill. However such a comparison is not always straightforward.

You are provided with values of surface pressure, surface temperature and rainfall at Palaiseau obtained from different sources:

- measurements performed at the SIRTA site over the period 2005-2009
- meteorological analyses (ERA-Interim ; see appendix) over the period 2005-2009
- a simulation of the period 1961-2000 by a climate model
- meteorological analyses (ERA-40 ; see appendix) over the period 1961-2000

Work :

1. *Comparison of SIRTA measurements and ERA-Interim analyses*.

Plot the pressure computed in the ERA-Interim analyses as a function of the pressure measured at SIRTA (this graph is called a scatter plot). Do you expect a perfect agreement ? Why ? How good is it in practice ? Compute the bias of the ERA-Interim analyses, their root-mean-square deviation from the SIRTA measurements, and their correlation coefficient with them. What do these quantities represent ?
Repeat the analyses with temperature and precipitation. What do you observe ?
Now pick a month of the year and repeat the analyses with data pertaining only to this month. Is this a more stringent skill test ?

2. *Comparison of a simulation of the recent climate and ERA-40 analyses*

Plot the temperature computed by the climate model as a function of the temperature computed in the ERA-40 analyses. How good is the agreement ? Repeat the analysis for a certain month of the year. Why is the agreement so bad ? Does such a skill test make sense for a climate model ?
Now compute and plot the statistical distribution (see appendix) of the ERA-40 temperature. Do the same with data from the climate model. Are they identical ? Does the climate model have a bias ?
Repeat your analysis with data pertaining only to a specific month of the year.

We encourage you to address the following questions in your report:

- What is an meteorological analysis ? Stress important differences with respect to a climate simulation.

- How much sense does it make to compare a local measurement to a model output ? Explain simple skill scores that you have computed and the orders of magnitude you have found.
- Among those scores which of them make sense to evaluate the skill of a climate model ? Why ?

Appendix

Analyses are meteorological fields produced by weather forecasting models. An analysis is the state of the atmosphere at a given time which is the most consistent with a large number of observations and with the constraints imposed by the laws of physics expressed in the weather forecasting model.

The European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/) operates a global weather forecasting model and provides the corresponding analyses. The ERA-40 reanalysis covers the period 1957-2001 (http://www.ecmwf.int/research/era/do/get/era-40) and the ERA-Interim reanalysis covers the period 1989-2009 (http://www.ecmwf.int/research/era/do/get/era-interim).

CHIMERE is a chemistry-transport model developed at LMD/IPSL used both for research purposes and operationnally to monitor and forecast air quality of many cities in France and Europe (http://www.lmd.polytechnique.fr/chimere/).